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Removal of Waste Anesthetics Exhaust

BY

S. H. C. Liang, D. G. Bailey*, R. T. Poirier and B. V. Lacroix

19980129 034

* Summer 1995 Defence Research Asisstant

December 1995

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SUFFIELD REPORT NO. 639

REMOVAL OF WASTE ANESTHETICS EXHAUST

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ABSTRACT

This report describes the use of Canadian military carbon-containing canisters (C2 and C7) in removing waste anesthetics exhaust. The efficiency and service-life of these canisters are presented. In addition, the use of other adsorbents and some commercially-available occupational health and safety canisters for this purpose is also discussed.

EXECUTIVE SUMMARY

TITLE

Liang, S.H.C., Bailey, D.G., Poirier, R.T. and Lacroix, B.V., "Removal of Waste Anesthetics Exhaust", DRES Report No. 639, December 1995.

INTRODUCTION

The current practice inside hospital operating rooms of allowing waste anesthetic (such as halothane) vapour to escape into the atmosphere is deemed unsafe for personnel and for the environment. This becomes a bigger problem in combat and mass casualty situations, or inside crowded operating rooms (such as those encountered in field hospitals). The accumulation of exhaled halothane will result in the exposure of personnel to potentially toxic levels of this material.

RESULTS

This report describes one approach in minimizing the waste anesthetic introduced into operating rooms by installing carbon-containing canisters downstream of the patient's exhaust and at the pop-off valve of the anesthetic machine. The service-life of the Canadian C2 military canister in removing halothane vapour under controlled conditions was found to be about 2 hours. Calculations show that the installed C2 canister would only impose minimal breathing resistance to the anesthetized patient. First-article Canadian C7 plastic high-performance canister was also evaluated; these were found to last about 3 hours under the same challenge conditions. Other kinds of activated carbon (e.g., different base carbons, different shapes and sizes etc.) and some commercially-available health and safety canisters were also evaluated. They were found to offer various levels of effectiveness in the removal of halothane. The preliminary results indicated that halothane is removed from the airstream by physisorption

EXECUTIVE SUMMARY (continued)

(i.e., retained on the carbon surface), thus chemical impregnation of the carbon does not improve its effectiveness in removing the halothane exhaust.

SIGNIFICANCE OF RESULTS

Currently, the Canadian Forces (CF) field hospitals employ efficient venting to remove waste anesthetics exhaust. The installation of Canadian C2 and C7 (in-service by 1997) canisters at the exhaust pop-off valve of anesthetic machines could effectively lower (or stop, with a canister replacement frequency of every 2 hours) the release of waste anesthetic vapours into the operating room. This will significantly improve the health and safety of medical personnel, and also lower the power requirement from the blower fans (to supply fresh air and to remove exhaust).

FUTURE GOALS

The experiments reported may not accurately reproduce the actual scenario (i.e. concentrations, temperature, humidities etc.) when waste halothane is produced by the anesthetized patient. Further work using realistic concentrations and conditions found in operating rooms will be necessary if charcoal filtration of anesthetic gases is to proceed.

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1.0 INTRODUCTION

Halothane has obtained widespread usage as an inhalation anesthetic since the 1950s. It has the advantages of being non-flammable and highly volatile. In replacing anesthetics employed earlier, such as ether and chloroform, the use of halogenated anesthetics has eliminated such hazards as fire, explosion and potential exposure to carcinogens inside hospital operating rooms. Other analogues of halothane, such as enflurane and isoflurane have also been used successfully as clinical anesthetics.

The current practice inside hospital operating rooms is to allow the waste anesthetics exhaust from the patient and the anesthetic delivery machine to vent directly into the atmosphere. Similarly, nitrous oxide, N_2O commonly used during dental operations, is excreted unchanged into the dental office. This practice is neither safe for the hospital personnel (if the room is poorly ventilated), nor environmentally friendly. It has been reported [1] that an average concentration of 10 ppm of halothane and 130 ppm of N_2O were found in air samples at various distances from the pop-off valve of anesthetic machines. Furthermore, up to 12 ppm of halothane was found in end-expired air samples taken from 24 anesthesiologists after work [1]. On the environmental side, it was suggested [2] that halogenated anesthetics may have the potential to cause stratospheric ozone depletion and global warming.

The average uptake of halothane by patients during an operation is 3-5 mL of the liquid per hour. During surgical anesthesia, arterial blood levels of halothane ranged from 80-260 mg/L; after anesthesia the patients were able to respond to verbal commands when arterial concentrations were 30 mg/L or less [3]. Although most of the halothane is eliminated during the 9 hour post-anesthetic period [3], approximately 80% of the total dose of halothane is excreted unchanged via the lungs [4]. This implies that during any operation, as much as 2-4 mL of liquid halothane may be exhaled by the patient into the operating room

per hour, assuming that the outlet valve on the anesthetic delivery machine is fully open (i.e., no recirculation within the anesthetic delivery machine). A simple calculation would show that inside a room with no circulation of air, and the patient breathing at a rate of 7.5 L/min (estimated for a patient under anesthesia - to be discussed in Section 2.2), 2 to 4 mL of halothane liberated per hour would correspond to a concentration of about 8000 to 16000 mg/m³ (1000 to 2000 ppm) of halothane exhaled from the patient. This number may appear high, because it assumes no circulation of air inside the room (causing a continual build-up of halothane) -- a case not normally encountered.

The established NIOSH (National Institute of Occupational Safety and Health) limit for waste anesthetic gases and vapours has a ceiling limit (CL) of 2 ppm/hour, while the ACGIH TLV (American Conference of Governmental Industrial Hygienists threshold limit values) for halothane is given by a TWA (time weighted average) of 50 ppm [5]. Thus, from the above calculation, it appears that a large amount of halothane vapour may be present in the operating room if the room is not properly ventilated. This becomes more of a problem in combat and mass casualty situations, or inside a crowded operating room (such as those encountered in field-hospitals). The accumulation of exhaled halothane (at about 1000 - 2000 ppm per hour) will result in the exposure of medical personnel to levels of halothane which may exceed the ACGIH TLV.

2.0 PROBLEM AT HAND

2.1 Removal of Waste Anesthetic Exhaust

It would be desirable to install a filter containing a suitable adsorbent (such as activated carbon) at the exhaust valve downstream from the patient, so that all exhaust anesthetics may be removed to avoid contamination of the operating and the post-operating rooms.

However, this is not a trivial problem. It is well known that most activated carbons cannot remove gases/vapours with low boiling points. Furthermore, some halogenated organic compounds which have moderate boiling points are not adsorbed onto activated carbon to an appreciable extent.

A search through open literature publications and patent applications revealed that there were at least two patents [6, 7] disclosing the use of activated carbon, or a combination of activated carbon and molecular sieve placed inside a cartridge for the removal of exhaust anesthetics. It seems that the removal of anesthetic exhaust may be achieved with a carbon-containing canister, but it has not been practised inside hospital operating rooms [8]. This may arise because the disclosures in the patents [6, 7] did not identify the specific adsorbents employed, nor the efficiencies of the elimination process.

Currently, Canadian Forces (CF) field hospitals employ efficient venting to remove waste anesthetics exhaust. It will be informative for the CF medical personnel to know if the current in-service gas-mask canisters (C2 or C7) may be employed for the same purpose. Installation of canisters at the patient's exhaust, or at the pop-off valve of the anesthetic machine may lower the release of anesthetics into the atmosphere. This will significantly improve the health and safety of medical personnel, and also lower the power requirement from the ventilation system. For completeness, this report will also comment on some commercially-available, off-the-shelf occupational health and safety carbon-canisters which may be used for this purpose. Their cost, effectiveness and service-life will also be detailed.

2.2 Breathing Resistance

Excessive resistance to breathing may lead to ventilatory failure. When a patient is under anesthesia and breathing through an apparatus, this constitutes an

additional hazard of obstruction to air flow. Putting a canister downstream from the anesthetized patient may remove the exhaust anesthetic, but it may also increase the breathing resistance. Table I summarizes the pressure gradient (breathing resistance) across a Canadian C2 canister containing ASC/T carbon at different flowrates [9].

Table I
Breathing Resistance Across a C2 Canister at Different Flowrates

Flowrate (L/min)	Breathing Resistance (kPa)
20	0.074
30	0.119
40	0.168
50	0.213
60	0.267
70	0.319
80	0.369
90	0.428
100	0.488
110	0.543

A flowrate of 20 L/min is the lowest obtainable flowrate in our laboratory. Assuming linearity also holds for the lower flowrates, the pressure drop (or, breathing resistance imposed on the anesthetized patient) across the canister may be estimated using the following linear regression model (with $R^2 = 0.998$), as shown in equation 1:

$$\text{Resistance (in kPa)} = 0.00523 \times (\text{Flowrate}) - 0.0409 \quad \text{Eqn \{1\}}$$

Thus, at a flowrate of 7.5 L/min (average for a patient under anesthesia - to be discussed later), the pressure drop across the canister is almost nil (0.039 kPa). Considering that the typical respiratory resistance for a healthy patient under anesthesia is of the order of 0.3 to 0.6 kPa [10], a canister downstream of the patient would produce no significant added breathing resistance (not more than 10%). The choice of a breathing flowrate of 7.5 L/min is arbitrary. Breathing rate varies from individual to individual, and depends on the various health and environmental conditions. Breathing rate ranging from 5 to 15 L/min is estimated for human beings at rest [3]. An average breathing rate of 7.5 L/min was chosen for patients under anesthesia in this study.

3.0 APPROACH TO THE PROBLEM

3.1 Existing CF Technology

3.1.1 The Canadian C2 Canister

The adsorbent employed inside the Canadian C2 canister is an activated carbon impregnated with 6-8% copper, 1-3% chromium, 0.05% silver and 1-3% triethylenediamine (TEDA). This carbon may be obtained from Calgon Carbon Corporation, PA, USA, under the trade name of ASC/T carbon. The carbon granules used in the canister have a size range of 12 to 30 US mesh, but the same carbon may also be obtained in other granular sizes.

The Canadian C2 canister is a good starting point for this project in removing waste anesthetic exhaust because:

- a. with a suitable adapter, this canister could be fitted onto the exhaust valve of the patient, or onto the anesthetic machine; and

- b. the ASC/T carbon employed in the C2 canister removes all acidic and some low boiling gases such as hydrogen cyanide, cyanogen chloride, phosgene, and chloropicrin, and thus may be possibly extended to halothane; and
- c. C2 canister is designed to have a maximum breathing resistance of about 0.12-0.15 kPa at a flowrate of 30 L/min, allowing comfortable usage by human; and
- d. there is an existing Canadian supply for the C2 canister at Racal Filter Technologies Inc. (RFTI) in Brockville, Ontario. Racal Filter Technologies also supplies a variety of occupational health and safety canisters. Therefore, larger diameter canister or canisters of other designs (to minimize breathing resistance) may be designed and manufactured at RFTI to suit the purpose of this application.

3.1.2 The New Canadian C7 Canister

The new C7 canister is configured in a dual-bed formulation: a bed of 125 mL penetrant protective carbon (PPC) on top of another bed of 125 mL of ASC/3T carbon (the 3T indicates that the content of TEDA is at least 3% by mass). The PPC was developed at Defence Research Establishment Ottawa (DREO) for the retention/removal of some toxic, low boiling organofluorine compounds which may penetrate a bed of ASC/T carbon [11]. The amine impregnant on PPC has been shown to react with certain organofluorine compounds to produce product(s) which are either innocuous or retained by the activated carbon. Consideration of the chemistry involved suggests that it is unlikely that the amine impregnant would react with the halothane. However, with the large surface area available on the PPC, the halothane may be physically retained by the carbon surface. Thus the PPC may be a viable candidate in removing halogenated anaesthetics from the patient's exhaust.

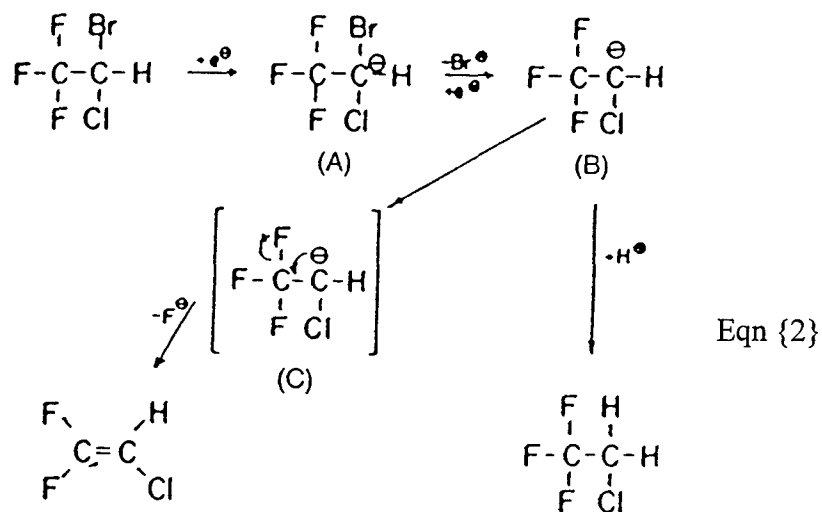
3.2 Oxidizing Catalysts

It is doubtful that the C2 canister containing ASC/T carbon would be able to remove or retain nitrous oxide (N_2O). However, filters containing oxidizing adsorbents are commercially-available, such as the CO-Filter 580 ST manufactured by Auer (MSA) in Germany. This filter contains Hopcalite (a mixture of MnO_2 , CuO , Co_2O_3 and Ag_2O) which oxidizes carbon monoxide to carbon dioxide at room temperature [12]. It is possible that this filter may be used to remove N_2O (by an oxidation reaction) from the exhaust of dental patients. A C2 canister coupled downstream to the Hopcalite-containing filter may be used to remove the oxidation products such as nitric oxide, NO and nitrogen dioxide, NO_2 .

3.3 Alternate Pathways

If ASC/T or PPC carbon is found to be ineffective or inefficient in the removal of waste anesthetic exhaust, other adsorbents or impregnants could be studied.

In order to find the appropriate adsorbent or an impregnant for the carbon surface, it is important to understand how halothane is metabolised in the human body. It is known [1] that halothane is degraded as a result of oxidative metabolism to Br^- , trifluoroacetic acid (TFA) and Cl^- . On the other hand, reductive metabolism results in 2-chloro-1,1,1-trifluoroethane (CTE) and 2-chloro-1,1-difluoro-ethylene (CDE), both volatile, and F^- , as shown below in equation 2 [1]:



All the metabolites have been identified directly in human urine or exhaled air following exposure to halothane. Thus, if it is required to boost the effectiveness of the carbon, specific impregnants to destroy the halothane could be sought.

4.0 EXPERIMENTAL

4.1 Material

4.1.1 Halogenated Anesthetics

Two halogenated anesthetics, halothane and isoflurane were used in this study. Their chemical structures are shown below and the properties [1] are summarized in Table II:

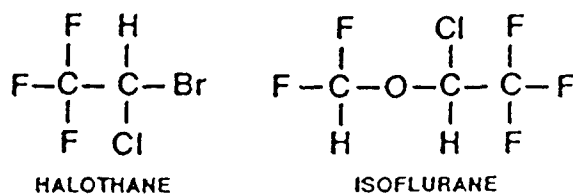


Table II
Properties of Some Halogenated Anesthetics

	Halothane	Isoflurane
Molecular Weight (g)	197.4	184.5
Boiling Point (°C) @ 101.3 kPa	50.2	48.5
Vapour Pressure (kPa) @ 20°C	32.1	31.7
Liquid Density (g/mL)	1.86 (20°C)	1.496 (25°C)
Vapour/Liquid (mL)	227	196
Chemical Stabilizer	Yes	No
Flammability Limits	None	None

Other halogenated anesthetics, such as enflurane and methoxyflurane have chemical structures very similar to isoflurane, and thus were not studied. Furthermore, methoxyflurane is flammable, and therefore is excluded from this study. The halogenated anesthetics used in this study were obtained from commercial sources. Halothane and isoflurane were procured from Wyeth-Ayerst Canada of Montreal, PQ, Canada, and Ohmeda Pharmaceutical Products, Mississauga, ON, Canada, respectively. The reagent bottle containing halothane also contains a stabilizer. This stabilizer appears as an oil in the pot heater after all the halothane is evaporated. The content of this stabilizer is estimated at 0.2% by mass.

4.1.2 Gas-Mask Canisters Employed

The following in-service or commercially-available gas-mask canisters were studied in this report:

- a. C2 canisters, Lot #4240-21-871-7842 (1986): These canisters were manufactured by Pall (Canada) Limited, and contain 170 mL ASC/T carbon. These were the gas-mask canister in service before 1989. These canisters, although more than ten years old, were stored in vacuum-sealed aluminum bags, and believed to suffer minimal ageing and performance degradation.
- b. Racal Health and Safety Group A:456-00-02 canisters: These were manufactured by RFTI, Brockville, ON, Canada. These canisters contain 225 mL of GMS-70 activated carbon produced by California Carbon Co Ltd.
- c. An experimental RD724950817-1-2 canister: These were manufactured by RFTI, Brockville, ON, Canada, also. These canisters contain 250 mL of the GMS-60 activated carbon produced by California Carbon Co Ltd.
- d. The first-article C7 canisters from RFTI, Brockville, ON: These canisters were supplied to DRES for quality assurance evaluation, and are not in-service items.

The ASC/T carbon has been described in Section 3.1.1. The GMS-60 and -70 carbons are unimpregnated activated carbons derived from coconut-shell.

4.1.3 Adsorbents Employed

There were several adsorbents investigated in this study:

- a. Calgon 12 x 30 US mesh BPL carbon: This is the coal-based precursor i.e., the non-impregnated carbon from which ASC/T (the impregnated carbon) is made. The 12 x 30 US mesh indicates that the carbon granules have a size range of 0.6 to 1.7 mm.

- b. Calgon 6 x 16 US mesh BPL carbon: This is the same BPL carbon as (a), except that the granular size is larger, i.e., from 1.18 to 3.35 mm.
- c. Norit RG-2 A5775 Carbon: This is a peat-based activated carbon which has been impregnated with copper, chromium and silver (i.e., the ASC variety), manufactured by Norit N.V., in the Netherlands. This carbon is procured in the extruded form of 2 mm in diameter and 6 mm in length.
- d. California GMS-70 Carbon: This is a coconut-shell based carbon mentioned above in Section 4.1.2 (b) used in the Racal occupational health and safety canisters.
- e. Carulite 200: This is an oxidizing catalyst manufactured by Carus Chemical Co, IL, USA. The major components of this Hopcalite-type catalyst consist of 60-75% manganese oxide, 11-14% copper oxide and 15-16% aluminum oxide.
- f. Penetrant-Protective Carbon (PPC): The Calgon BPL carbon mentioned in (a) above was first treated with 7 - 10% KOH, followed by an impregnation procedure with 7% triethylamine. The preparation and properties of the PPC has been described in a patent application [11].

When adsorbents are used inside gas-mask canisters for air-filtration purpose, several properties become important. For example, the distribution of particle size and the hardness of the adsorbent will determine the breathing resistance across the canister. The particle size distribution of the adsorbent determine the packing of the adsorbent granules, and thus the void space inside the canister. The hardness of the adsorbent granules determines how much the granules are "crushed", and then fill up the void space. Both factors control the breathing resistance of the canister. The bulk density of the adsorbent determines

the amount of adsorbent which may be packed inside a canister. These are important physical properties which contribute to the effectiveness of the adsorbents when used inside gas-mask canisters. Table III summarizes some of the relevant physical properties of the adsorbents studied in this report.

Table III
Some Physical Properties of Adsorbents Used in this Study

	Norit RG-2 ASC	Calgon BPL 12 x 30 US Mesh	Calgon BPL 6 x 16 US Mesh	Canada PPC 12 x 30 US Mesh	Calgon ASC/3T 12 x 30 US Mesh	GMS-70
Bulk Density (g/mL)	0.49	0.49	0.51	0.51	0.65	0.45
Sieve Analysis						
Mesh 6			0.3			
Mesh 8			38.8			
Mesh 12		0.0	39.2	0.0	0.0	0.0
Mesh 16		41.7	17.3	57.3	46.4	77.0
Mesh 20		26.7	3.3	28.4	30.9	19.3
Mesh 30		29.4	0.1	13.1	21.7	3.5
Mesh 72		1.6	0.5	0.5	0.1	trace
Retainer		0.2	trace	trace	trace	trace

4.1.4 Custom-Made Canisters

To evaluate the performance of the adsorbents described from (a) to (f) in Section 4.1.3, the adsorbents were first loaded into a C2 canister body up to a volume of 170 mL. A fines-filter and the top retainer were then mounted on top of the carbon bed. This constituted a half-body C2 canister. This is called half-body canister because it does not contain a HEPA (high efficiency particulate filter) filter to complete a C2 canister.

Half-body C7 canisters were prepared by adding 125 mL of a penetrant-protective carbon (PPC) on top of 125 mL of ASC/3T carbon inside the C7 plastic canister. The fines-filter and the top retainer were then mounted and ultrasonically welded onto the canister body. This constituted a half-body C7 canister. These canisters were made at DEO in February 1993, and were stored inside vacuum-sealed aluminum bags.

4.2 Description of the Experimental Set-Up

A brief description is given here and Section 4.3 to illustrate the vapour-challenge apparatus and the procedure of producing challenge vapours which have to be vaporized from the liquid state, such as halogenated anesthetics employed here. A description on the gas-phase introduction of challenge gas has already been published [13].

Figure 1 shows a schematic of the apparatus (or the "challenge-rig") and the flow path of air and the test gas. The Miller-Nelson HCS-301 instrument, 1 controls the relative humidity (RH), temperature and flow rate of air going into the system. The test liquid (halothane or isoflurane) is withdrawn from its container 2 using a peristaltic pump, 3 into a pot heater 4 where it is vaporized and combined with the pre-humidified air supplied from 1. The mixture of air and challenge vapour is then introduced into a baffle mixer 5 where the mixture is thoroughly mixed. The challenge vapour/air mixture is then let into the test chamber 6, where the canister being testing is situated. After passing through the filter, the effluent is diverted into two streams: the major stream passes through another canister, 8 (the scrubber) for the removal of test gas before the remaining airstream exits into the fumehood. The minor stream passes into a gas chromatograph 13, (controlled at about 100 mL/min with a metal-bellow pump, 12) so that the effluent can be properly analyzed. A quantitative reading of the amount of test gas in the effluent is obtained using the integrator 14.

Figure 2 shows the picture of the complete vapour challenge apparatus inside the fumehood, where the experiments took place. The greyish/blue object at the lower left corner is the metal bellows pump, drawing the effluent into the gas-chromatograph placed outside the fumehood. Figure 3 is a close-up of the front of the apparatus. It shows the Tygon tubing coming off the top of the halothane bottle. The pot heater, 4 and the baffle mixer, 5 can be seen on the left hand side of the picture. Figure 4 shows the challenge chamber in the open state (to be described below); the canister in front is the test canister, while the canister in the back is the scrubber.

4.3 Details of Component Parts

4.3.1 Air Supply

A Miller-Nelson HCS-301 Flow-Temperature-Humidity controller, 1, procured from Miller-Nelson Research Inc, CA, USA, is used to generate a constant air flow of 22.5 or 30 L/min ($\pm 2\%$) at ambient temperature, $25^{\circ}\text{C} \pm 1\%$, and a RH of $80\% \pm 3\%$. The flow, temperature and RH are monitored daily (and sometimes between experiments). The flow rate is checked with a dry test meter from Parkinson-Cowan, while the relative humidity is calibrated at 84.3% and 52.9% (25°C) with saturated solutions of potassium chloride and magnesium nitrate respectively. The temperature sensors are adjusted to comply with an NBS (National Bureau of Standards) thermometer by manipulating the bias voltages of the thermocouple.

4.3.2 Supply of Challenge Vapour

There are various ways by which the challenge liquid can be introduced into the test chamber as a vapour mixed with air. For halothane and isoflurane, the challenge liquid was withdrawn from the reagent bottle via a Cole-Parmer

Masterflex microprocessor pump drive through silicone tubing. It was then discharged into the pot heater. This has been shown in Figure 3. Teflon tubing was found to swell upon prolonged use, and was deemed to be inappropriate for the experiment. The pumping rate and the calculation of the amount of halothane used is shown in Section 4.4. The pot heater was set at about 40°C (42°C for isoflurane) so that all the introduced halothane or isoflurane was vaporized. The challenge vapour was then mixed into a stream of pre-humidified air and exited from the pot heater into a T-junction. The majority of the air/halothane mixture was collected into a scavenging bottle, while a smaller stream at 7.5 L/min enters into the baffle mixer and then into the challenge chamber. The 7.5 L/min flow is monitored with a flow-meter.

4.3.3 Test Chamber Assembly

An expanded view of the test chamber assembly is shown in Figure 4. The test chamber assembly consists of two stainless steel cups which are operated by safety switches (both hands are required to bring the cups down). The cups are operated by pneumatic pistons at 413 kPa (60 psi), and the O-rings at the bottom plate assures a good seal. The switches are designed so that there is a separate control for each stainless steel cup. The cup at the back (i.e., the secondary chamber, 8 in Figure 1) contains the scrubber canister to remove all chemicals (toxic or not) before the effluent is released into the fumehood.

4.3.4 Canister Effluent Analysis

The concentration of halothane (or isoflurane) which has penetrated through the canister is monitored by a Hewlett-Packard HP5890 gas chromatograph (GC) equipped with a flame-ionization detector (FID). Flame-ionization detection is standard in the detection of organic chemicals at very low concentration (nanogram region). A 100 mL/min sample is drawn downstream from the canister by a metal-bellow MB21 pump into the GC. The sample passes

through a 12 meter long, 0.53 mm diameter DB-1 column before being introduced into the FID.

The detected signal from the FID is then converted into a digital signal by means of a Hewlett-Packard 3393 integrator. From careful calibration of the digitised signal with standard diluted samples of halothane, the breakthrough concentration of 16 mg/m^3 could then be monitored. These standards were prepared by introducing various amounts of halothane into Tedlar Bags, and then diluting with known amounts of nitrogen.

4.4 Typical Calculation of the Concentration of the Challenge Vapours

Halothane will be used as an example here. A desired amount of halothane is withdrawn from the reagent bottle into a pre-weighed vial fitted with a rubber septum. This amount is calculated for experiments which last about 8 hours using 5 mL of halothane per hour ($= 5 \times 8 \times 1.86 = 17 \text{ gram}$, where 1.86 is the density of halothane). A syringe connected to the Masterflex microprocessor pump via silicone tubing is then inserted inside the vial through the rubber septum to withdraw the halothane. By weighing the vial before and after (to determine the exact mass of the halothane used), and the duration of the withdrawal, the rate of halothane delivery (in g/min) could be determined. This delivery rate is then adjusted before and after each experiment to meet the required delivery rate shown below.

The desired concentration of halothane at the canister during the challenge experiments is 10000 mg/m^3 in an airflow of 7.5 L/min . Therefore the delivery rate of halothane vapour has to be set at 75 mg/min ($= 10000 \text{ mg/m}^3 \times 7.5 \text{ L/min} \times 10^{-3} \text{ m}^3/\text{L}$). Because the Miller-Nelson is designed to deliver flowrates of air from 20 to 30 L/min only, a higher delivery rate is required so that it can then be "geared" down to the desired delivery rate, as discussed in Section 4.3.2. This requires a halothane delivery rate of 225 mg/min ($= 22.5/7.5 \times 75 \text{ mg/min}$) to be

maintained.

4.5 Challenge Experiments

4.5.1 Test Adsorbents and Canisters

The C2, C7 and the commercially-available canisters were evaluated as is without any conditioning or prehumidification. The adsorbents (including activated carbons) were made into half-body canisters using the C2 or C7 canister body, as described in Section 4.1.4.

4.5.2 Challenge Conditions

The following conditions were used for the vapour-challenge experiments with halothane and isoflurane:

Challenge Concentration:	10000 mg/m ³
Flow rate:	7.5 L/min
Temperature:	Ambient
Relative Humidity:	80%
Breakthrough Concentration:	16 mg/m ³
Canister Used:	As indicated

While the average human breathing rate is about 30 L/min, it is expected that this rate will be much lower when the patient is under anesthesia. Thus a flowrate of 7.5 L/min is chosen. It has been stated in Section 1.0 that as much as 2-4 mL per hour of liquid halothane may be excreted unchanged from the patient's lung while the patient is anesthetized. This dosage is estimated to correspond to an inlet concentration of 10000 mg/m³ under a flowrate of 7.5 L/min. The breakthrough

concentration is set at 16 mg/m^3 ($= 2 \text{ ppm}$), the ceiling limit established by NIOSH for waste anesthetic gases and vapours per hour. A relative humidity of 80% is probably too low for human breath, but this humidity could be achieved easily without the problem of condensation inside the challenge apparatus and all associated lines.

4.6 Safety Considerations

All experiments were carried out inside a Class A fumehood with carbon filters at the exhaust. All personnel were briefed on the toxicity of halothane and isoflurane at various quantities. All precautions, safety and containment procedures including accidental spill, evacuation procedure etc., followed the DRES Safety Manual.

5.0 RESULTS AND DISCUSSIONS

5.1 Breathing Resistance Across the Canisters

It has been pointed out in Section 2.2 that one of the main concerns in this study is the extra breathing resistance imposed on the patient by the installation of scavenger carbon canisters. The following table summarizes the breathing resistance (pressure drop) across the canisters used in the experiments:

Table IV
Breathing Resistance (kPa) Across the Canisters Used in this Study

Flowrate (L/min)	Calgon 6x16 mesh	C7 half-body	GMS-60	GMS-70	Norit Extruded	C2 ASC/T
20	0.017	0.067	0.053	0.055	0.014	0.071
30	0.025	0.108	0.083	0.090	0.025	0.115
40	0.032	0.149	0.118	0.127	0.032	0.163
50	0.040	0.188	0.150	0.161	0.041	0.205
60	0.047	0.231	0.186	0.201	0.049	0.250
70	0.056	0.274	0.224	0.243	0.058	0.299
80	0.062	0.314	0.260	0.281	0.065	0.345
90	0.068	0.359	0.302	0.325	0.075	0.394
100	0.075	0.404	0.345	0.265	0.083	0.444
7.5*	0.0083	0.0125	0.0220	0.0234	0.0046	0.0102

These data were measured at DRES, i.e., at an ambient absolute pressure of 93 kPa (versus the 100 kPa at Ottawa). Thus the breathing resistances given here for C2 canister containing ASC/T carbon appears to be lower than the ones given in Table I. Using similar linear regression models (as in equation {1}), the breathing resistance across these canisters at a flowrate of 7.5 L/min may be estimated, as shown by the values in (*) Table II.

All the carbons tested are granular, with a nominal size ranging from 12 to 30 US mesh, except the 6 x 16 US mesh size carbon from Calgon Carbon Corporation. It is believed that larger granular size will effectively lower the breathing resistance of the canister. This has been demonstrated from the results

in Table II: data from column 2 were significantly lower than the rest of the carbons. Of special interest is the Norit ASC carbon which has an extruded form (cylindrical with 2 mm in diameter, and a nominal length ranging from 4 to 7 mm). The breathing resistance data measured for this carbon (given in the second last column of Table II) was the smallest observed for all the carbons investigated.

Thus it may be concluded that all the canisters (and thus all the carbon adsorbents) would not contribute significantly to the breathing resistance of the patient under anesthesia.

5.2 Experiments With Halothane

5.2.1 C2 Canisters Containing ASC/T Carbon

The breakthrough experiments involving halothane on C2 canisters were repeated ten times. Typical breakthrough profiles of halothane through the Canadian C2 canister containing ASC/T carbon are shown in Curves #1 to #10 in Figure 5. Not all breakthrough curves are shown to avoid crowdedness. The average breakthrough time was 137 ± 27 minutes, with the data ranging from 111 to 177 minutes. The wide range (spread) of data was to be expected, because:

- a. activated carbon, like all heterogeneous materials, are not uniform in terms of the distribution of surface functional groups and morphologies. The additional impregnation further complicates the surface uniformity; and
- b. the canisters containing the carbon had been around for ten years, and may have experienced various levels of ageing, thus the performance of these canisters may be variable; and
- c. while it is improbable, there may be fluctuations in the concentration of the halothane during the production of the vapour in the challenge apparatus. Changes in temperatures in the pot-

heater, or a slight change in the pumping (delivery rate of the halothane) may severely affect the inlet concentration, and thus the breakthrough time.

One interesting feature of breakthrough profiles is that there was always a sharp rise in the concentration of halothane penetrating through the canister after the breakthrough concentration of 16 mg/m^3 had been reached. However, the time to time it took to reach the "sharp" vertical rise may be quite fast (see, for example, #5), as opposed to some which rose more slowly, for example, #1.

These initial experiments established that activated carbon may be used to remove halothane for at least 2 hours under these experimental conditions.

5.2.2 Half-Body C7 Canisters Containing Dual Beds of PPC and ASC/3T Carbons

These canisters were experimental C7 canisters using a dual bed configuration of PPC on top of the ASC/3T carbon. They were made at DREO in 1993, but were stored in vacuum sealed bags. Three repetitions were performed, as shown in the breakthrough profiles #1 to #3 in Figure 6.

The average breakthrough time for the half C7 canister is 149 ± 5 minutes. The longer breakthrough time (service-life) was not surprising because the C7 canister contains more activated carbon (250 mL in total). Furthermore, the carbons used in these canisters are "fresher", and are therefore expected to have a better performance.

5.2.3 Half-Body C2 Canister Containing Calgon 12 x 30 US Mesh BPL Carbon

The breakthrough profiles of halothane through these canisters are shown in Figure 7. Although only two canisters were tested, the breakthrough profiles

were reasonably close together. The average breakthrough time was 134 ± 12 minutes.

The average breakthrough time for the BPL carbon is very close to the 137 minutes observed for ASC/T carbon. This indicates that the presence of metal impregnants offers little enhancement of performance against halothane. This confirms that the removal of halothane by the carbon surface is a physisorption process.

5.2.4 Half-Body C2 Canister Containing Calgon 6 x 16 US Mesh BPL Carbon

This special size carbon was evaluated because it was believed that the larger granular size will yield lower breathing resistance. The reduction in breathing resistance was demonstrated in Section 5.1.

There were only two experiments conducted for this carbon. The breakthrough profiles of halothane through this carbon are shown in Figure 8. The average breakthrough time was calculated to be 125 ± 35 minutes. This value is comparable with that observed for BPL and ASC/T carbon.

Thus the Calgon 12 x 30 mesh BPL carbon was not investigated further because since both Calgon (6 x 16 and 12 x 30 mesh) BPL carbons exhibited comparable performance. A lower breathing resistance, the 6 x 16 mesh carbon is definitely a better choice.

5.2.5 Half-Body C2 Canister Containing Norit ASC-Type Carbon

The breakthrough profiles of halothane through these canisters are shown in Figure 9. The average breakthrough time was 118 ± 32 minutes, significantly lower than that observed for Calgon ASC/T carbon or the BPL carbon. Thus, Norit ASC-type carbon was not investigated further.

5.2.6 Half-Body C2 Canister Containing the California GMS-70 Carbon

The breakthrough profiles for this carbon are shown in Figure 10. The mean breakthrough time was 157 ± 61 minutes. This carbon was shipped to us from RFTI without details of prior history. Thus the carbon may be quite old. Because of the wide spread of data, this carbon may not actually offer a significantly enhanced performance over the Calgon BPL carbon.

The precursor of this California carbon is coconut-shell procured from Sri Lanka. It is well known that coconut-shell based carbons have higher surface area and pore volumes than the coal-based (Calgon) or peat-based (Norit) carbons, therefore a higher adsorption capacity for halothane is not surprising for this California carbon.

5.2.7 Half-Body C2 Canister Containing Carulite 200

Four repeated experiments showed that there was immediate penetration of halothane through the canister containing Carulite, even after a drying procedure before the challenge experiment (to remove adsorbed water). It is well known [12] that Hopcalite-type catalyst is easily poisoned by the presence of water. This adsorbent was not investigated further.

5.2.8 Experimental Canisters from Racal Filter Technologies Containing the California GMS-60 Carbon

Due to the limited availability, only two canisters were tested against halothane. There were no observable penetration of halothane up to a total challenge time of 300 minutes. The carbon in this canister offered the best result

so far. This is to be expected since these canisters contain 250 mL (about 50% more carbon than the regular C2 canister) of a highly adsorptive carbon which is coconut-shell based. This combination offers the best solution in removing waste halothane exhaust.

5.2.9 First Article C7 Canisters

Only two of these full canisters (carbons plus particulate filter) were tested against halothane. Both canisters showed no penetration of halothane in challenge experiments up to 300 minutes.

It is not immediately obvious why these canisters performed better than the half-body C7 canisters tested in Section 5.2.2. The "freshness" of the carbon contained inside these canisters may be a contributing factor. Noting that there was always some spread of breakthrough profiles, further investigation with in-service items is necessary. C7 canisters will become an in-service item by 1997 when the current stock of C2 canisters is used up. More experiments with halothane on the C7 canisters will be performed by then.

5.2.10 C2 Canisters Containing ASC/T Carbon Challenged Under Various Conditions

The experimental conditions employed in this study were not ideal. The concentration of 10000 mg/m³ at an air flowrate of 7.5 L/min were estimations, and may not represent the typical mean values for patients under anesthesia. Similarly, the conditions of 30°C and 80% RH were limited by the equipment used. It would be expected that human expired air would have a temperature of about 37°C and a relative humidity close to 100%.

Three combinations of halothane concentrations and flowrates were used to test the dynamic adsorption capacity of the C2 canister containing ASC/T

carbon. These conditions were:

- a. 15000 mg/m³ at 7.5 L/min;
- b. 7000 mg/m³ at 7.5 L/min; and
- c. 10000 mg/m³ at 13 L/min.

These conditions are by no means exhaustive of all possible conditions encountered during the administration of halothane. However, they will give an indication on how the C2 canister will behave. The breakthrough profiles of these three conditions are shown in Figure 11. The "mean" breakthrough profile for halothane at 10000 mg/m³ and 7.5 L/min was estimated and inserted into the figure. The breakthrough time is indicated on each profile. As would be expected, increasing the halothane concentration or the flowrate of the challenge vapour decreased the breakthrough times. There was an obvious improvement in the breakthrough time when the concentration was decreased. Lowering the flowrate below 7.5 L/min is difficult to control, and therefore was not studied here.

5.2.11 Summary of Results

From the results obtained in this section, it has been shown that the canisters containing GMS-60 and -70 carbons offered the best performance i.e., the highest dynamic adsorption capacity for halothane. This definitely indicated that carbon with high adsorption capacity (such as the coconut-shell based carbon) performed the best against halothane. Both Canadian military canisters (C2 and C7) offered reasonable retention of halothane in these experiments. It is noted that metal impregnation of carbon does not improve the carbon in the removal of halothane.

5.3 Experiments With Isoflurane

After the success with halothane, it was a firm belief in this laboratory that the results obtained using C2 and C7 canisters would apply equally to isoflurane. To demonstrate this, several experiments were successfully carried out using isoflurane, the anesthetic of choice for the CF.

5.3.1 C2 Canisters Containing ASC/T Carbon

Only one challenge data was obtained for C2 canister containing ASC/T carbon against isoflurane, because of the average performance of the same canister against halothane observed in Section 5.2. The breakthrough time was estimated at 75 minutes. The decrease in the breakthrough time is significant. Obviously the difference in chemical structures between isoflurane and halothane contributes to the decrease.

5.3.2 Half-Body C2 Canister Containing Calgon 6 x 16 US Mesh BPL Carbon

The breakthrough profiles of these canisters when challenged with isoflurane are shown in Figure 12. The average breakthrough time was 95 ± 4 minutes. The observed breakthrough time for isoflurane was shorter than that for halothane, indicating that this 6 x 16 mesh carbon has a lower adsorption capacity for isoflurane. This was attributed to the differences in chemical structure given above. However, the average breakthrough time observed here (95 minutes) was higher than the 75 minutes observed for the ASC/T carbon (Section 5.3.2). The reason for this is not immediately obvious. It is well known that as much as 22% of the total surface area on the carbon is lost upon impregnation [14]. It seemed that the metal impregnants on the ASC/T carbon may be occupying some of the adsorption sites which are also available for the adsorption for isoflurane, thus decreasing the observed breakthrough time.

5.3.3 First Article C7 Canisters

Three challenge experiments with isoflurane were carried out with the first article C7 canisters. Breakthrough time was observed at 278 minutes for one canister, and for the other two, there was no observable penetration of isoflurane up to 300 minutes. Thus, C7 canisters perform very well against both the halothane and isoflurane.

5.3.4 The Experimental Racal Canisters Containing GMS-60 Carbon

Three canisters were challenged with isoflurane. Except one which broke at 174 minutes, the other two showed no trace of isoflurane up to 300 minutes. The wide spread of data requires further investigation.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Applicability and Availability

It has been demonstrated in this study that:

- a. The Canadian military C2 canister (containing ASC/T carbon) and the C7 canister (containing a combination of PPC and ASC/3T carbon) are capable of removing waste halothane and isoflurane vapour.
- b. The C7 canister performs better than the C2 canister in removing both halothane and isoflurane vapours.
- c. The metal impregnants on the carbon surface are not important in the removal of these two vapours.
- d. Commercial canisters containing a coconut-shell based carbon obtained from RFTI also performed very well against both halothane and isoflurane.

- e. The canisters mentioned in (a) and (d) are readily available within Canada. The C7 will be replacing the C2 canister, and will be an in-service item by 1997.

6.2 Determination of Realistic Challenge Conditions

The conditions employed in these experiments, such as a concentration of 10000 mg/m³ or an RH of 80% may not represent the actual scenario. Furthermore, the removal of halothane by activated carbon is a physical adsorption process. This process may be compromised by the presence of water and other organic vapours. This is because these vapours also adsorb onto the carbon surface, and compete with halothane molecules for the available adsorption sites. It is desirable that a determination of realistic conditions which are present in hospital operating rooms be made.

6.3 Recovery of the Anesthetics

The removal of halogenated anesthetics by activated carbon (impregnated or not) is a physical adsorption (physisorption) process. In processes like this, no chemical reaction occurs between the carbon surface and the halothane (or isoflurane) molecules - the adsorbates. The physisorption process is physical in nature, because the adsorbate molecules were held (retained) onto the carbon surface by physical forces such as the van der Waal's force. This implies that the force holding the adsorbates on the carbon surface is weak, and that the adsorbates may be made to desorb from the carbon surface by external forces (such as vacuum, heat, etc.). Thus the waste halogenated anesthetics picked up from patient's expired air by activated carbon should be recoverable from the carbon.

6.4 Service Life

It has been demonstrated in this study that C2 and C7 canisters can be used to remove waste anesthetic vapour. If it is decided to use these canisters for this purpose, a study involving a greater number of canisters should be carried out to establish accurate canister change times. For operations which may last beyond two hours, bigger canisters such as the C4 (carbon capacity of 297 mL), or two or three C2 canisters may be installed in tandem to provide longer service life.

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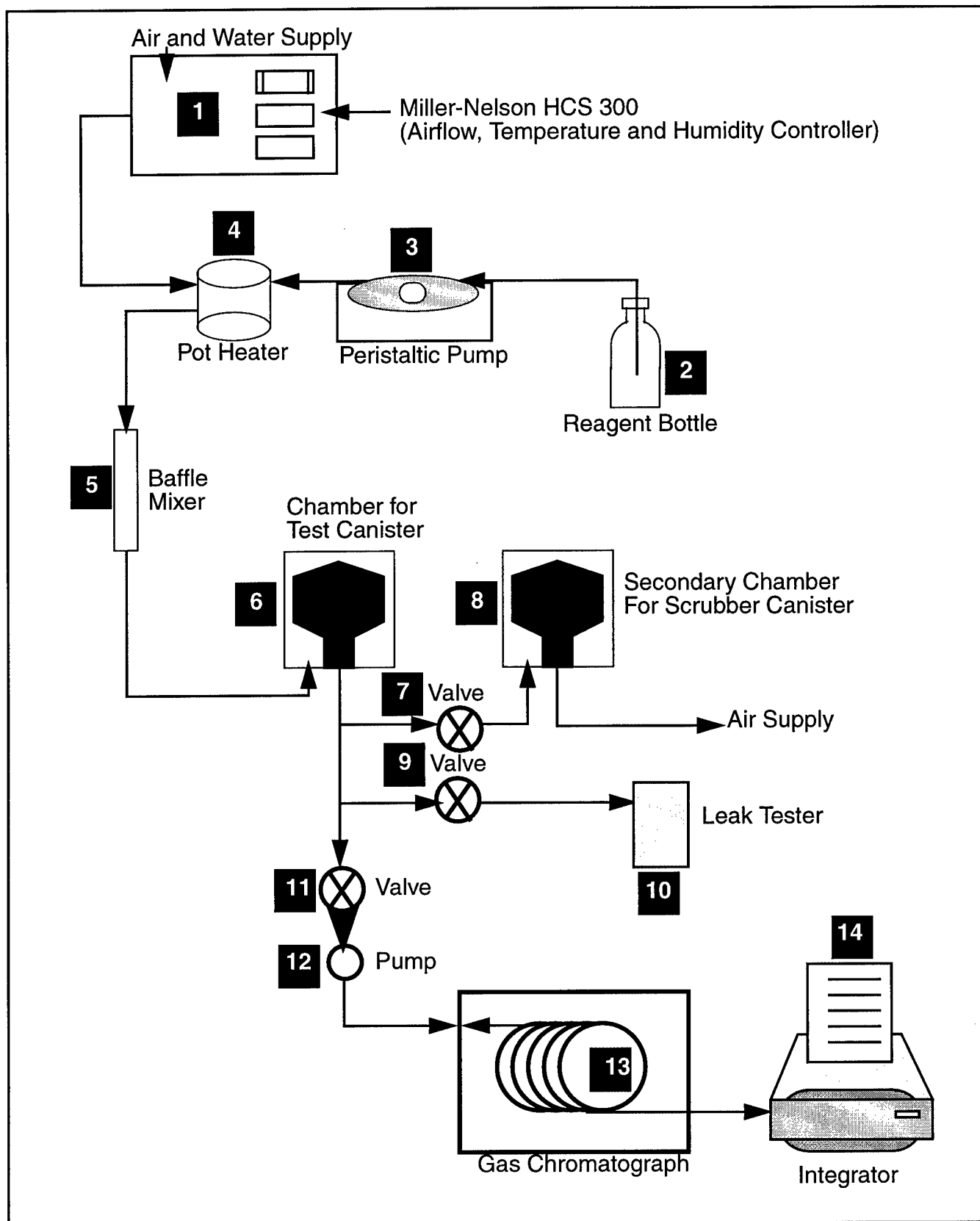


Figure 1

Block Diagram of the Vapour Challenge Apparatus and Peripheral Equipment

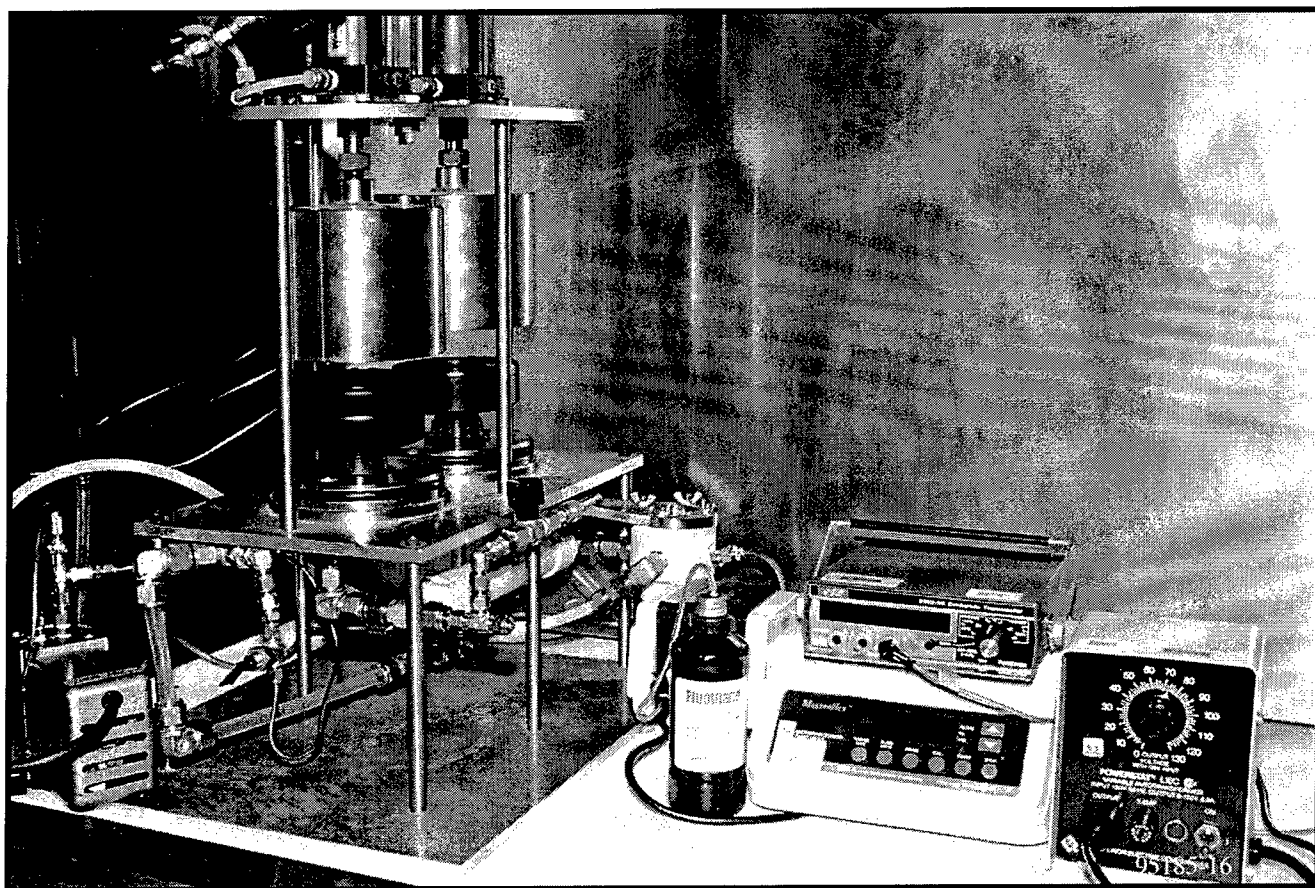


Figure 2

Picture of the Vapour Challenge Apparatus



Figure 3

Close-up View of the Front of the Vapour Challenge Apparatus

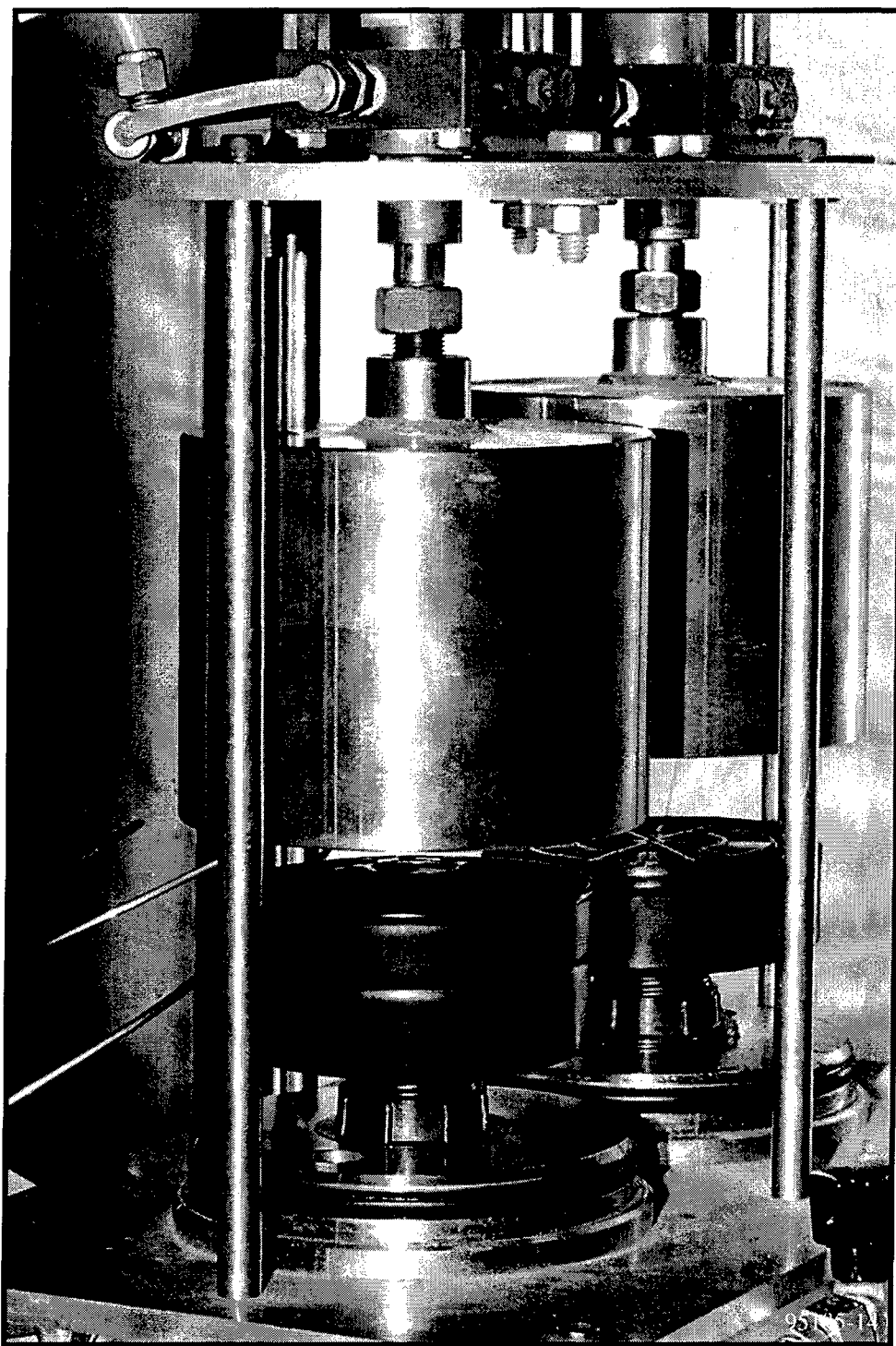
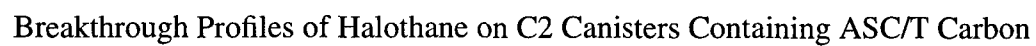


Figure 4

Blow-up View of the Test Chamber



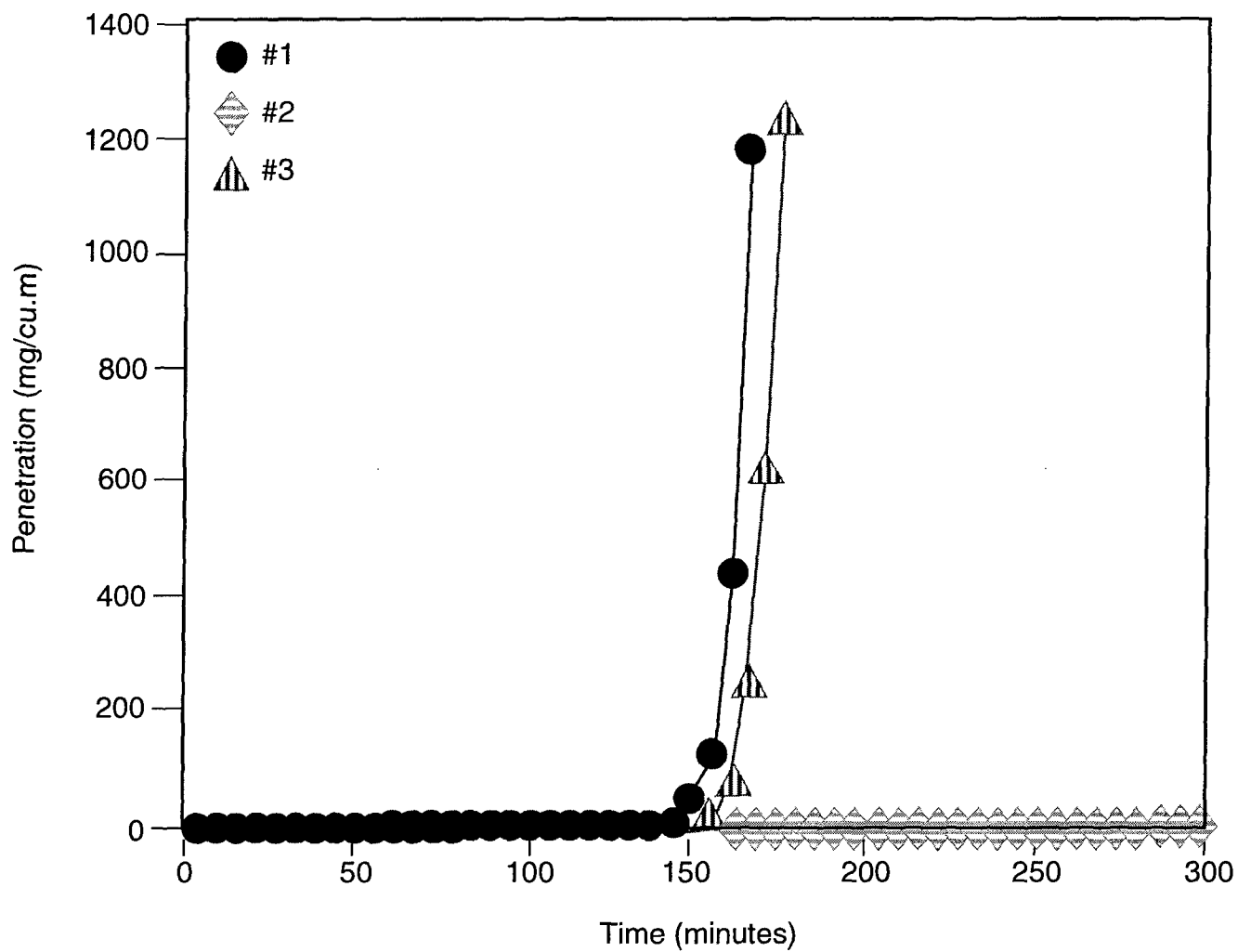


Figure 6

Breakthrough Profiles of Halothane on Half-Body C7 Canisters Containing Dual Bed of PPC and ASC/3T Carbon

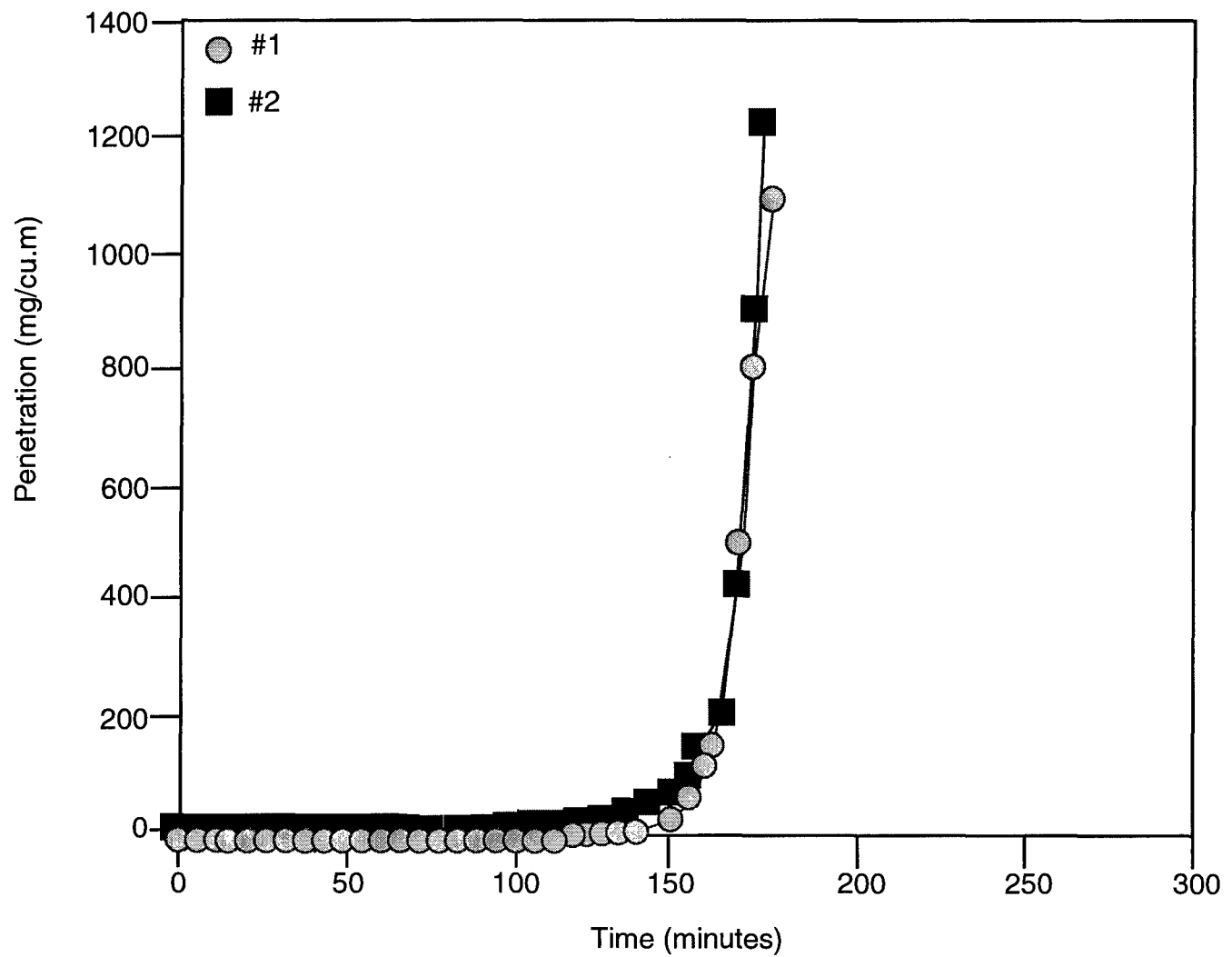


Figure 7

Breakthrough Profiles of Halothane on Half-Body C2 Canisters Containing
12 X 30 Mesh BPL Carbon

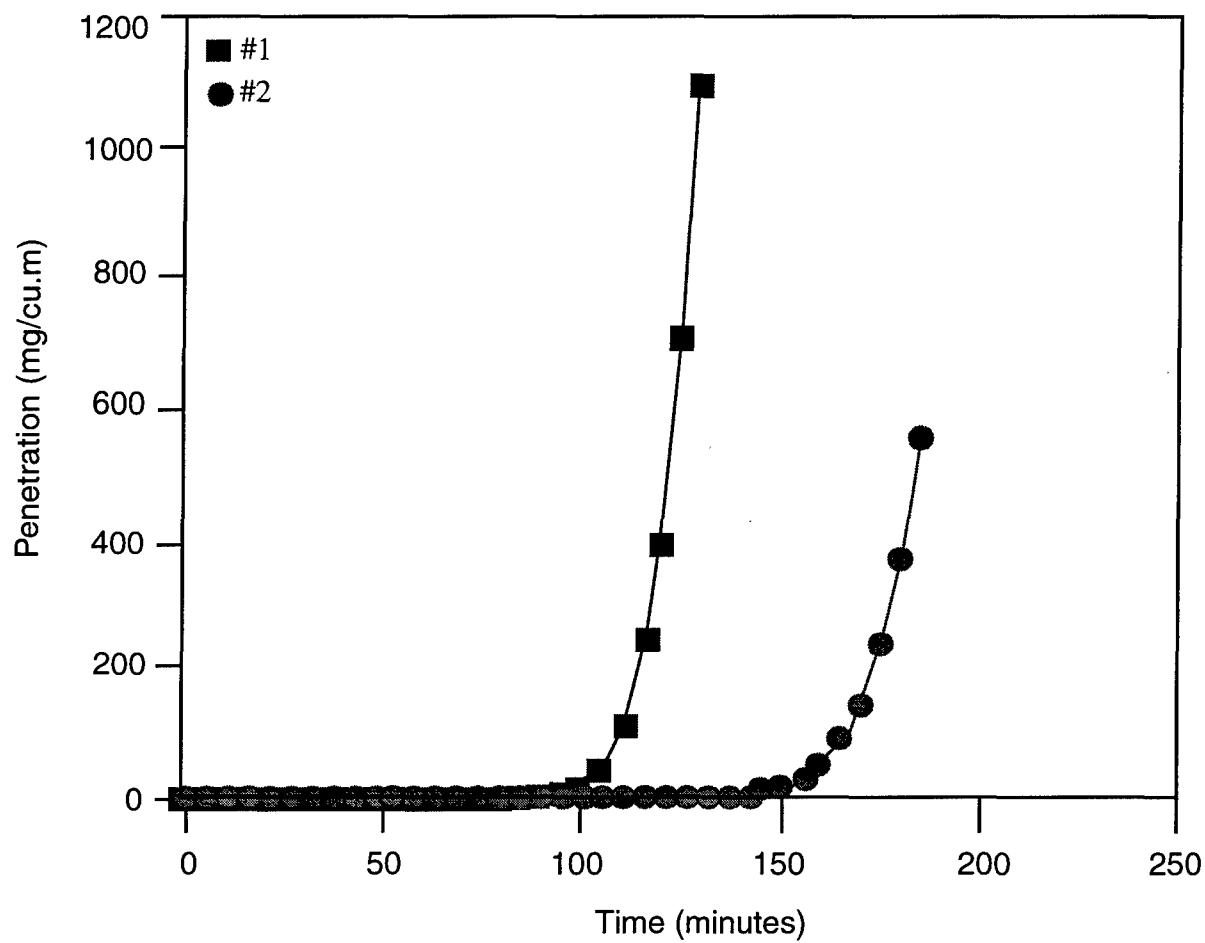


Figure 8

Breakthrough Profiles of Halothane on Half-Body C2 Canisters Containing
6 X 16 Mesh BPL Carbon

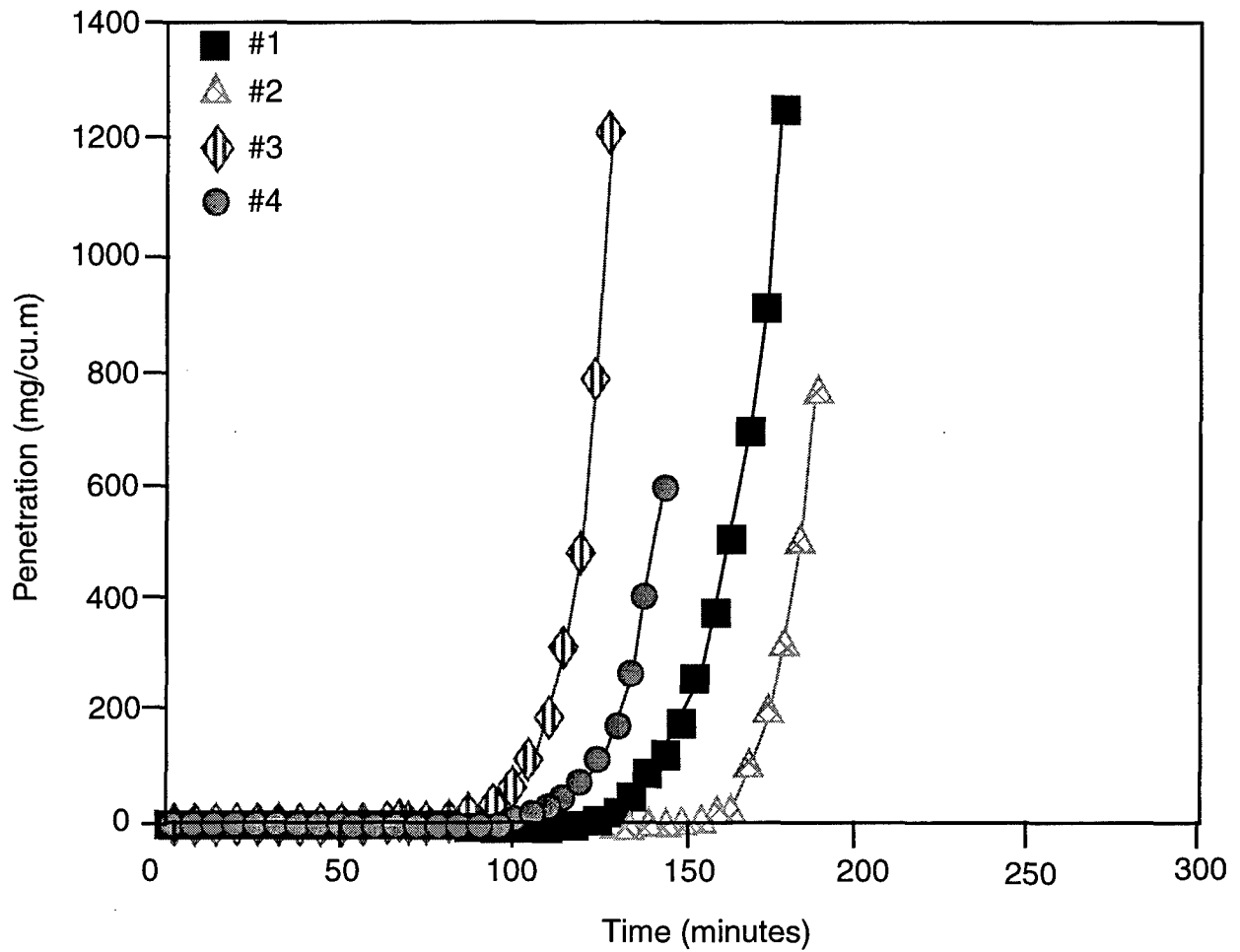
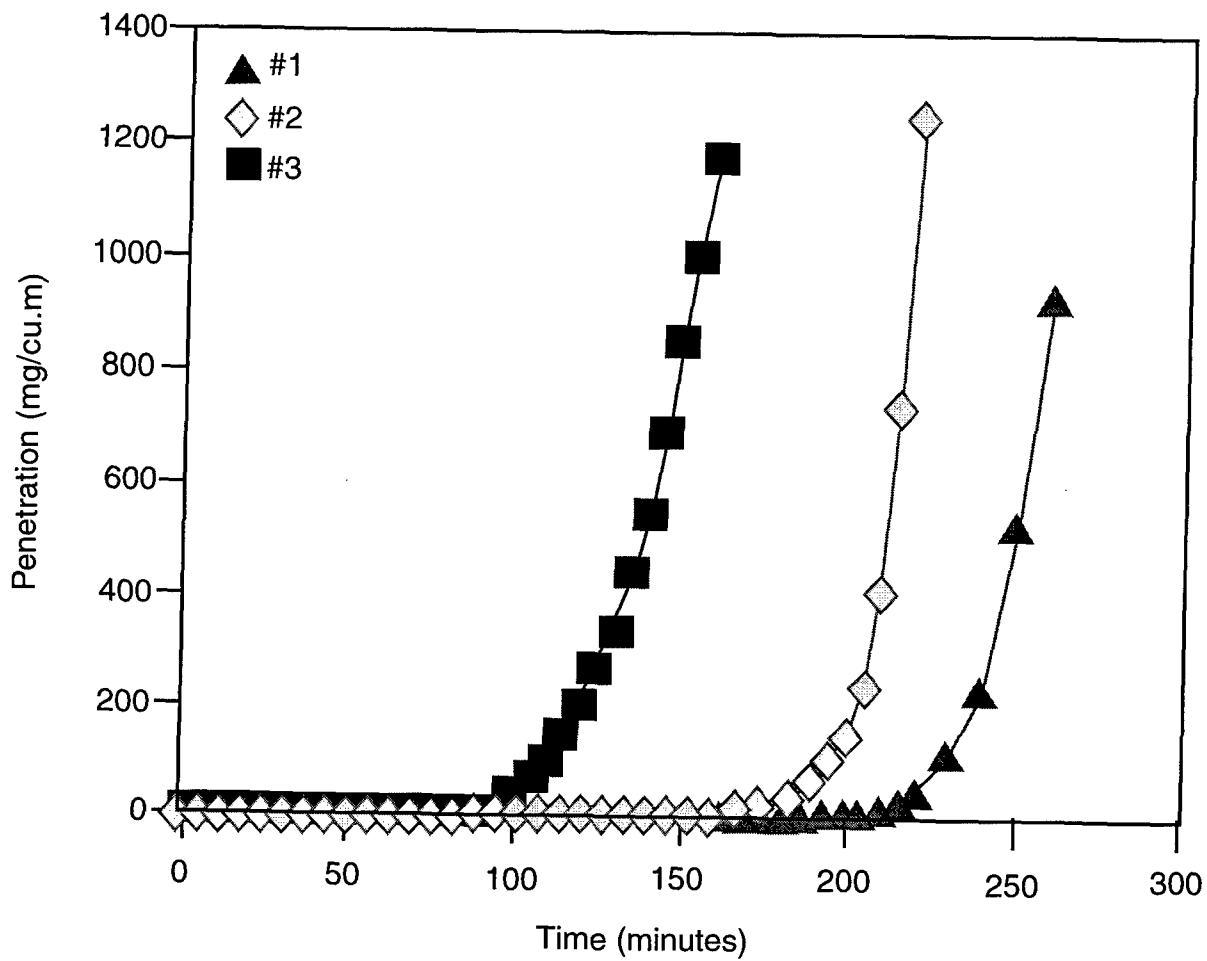


Figure 9

Breakthrough Profiles of Halothane on Half-Body C2 Canisters
Containing Norit ASC Carbon

UNCLASSIFIED**Figure 10**

Breakthrough Profiles of Halothane on Half-Body C2 Canisters
Containing GMS-70 Carbon

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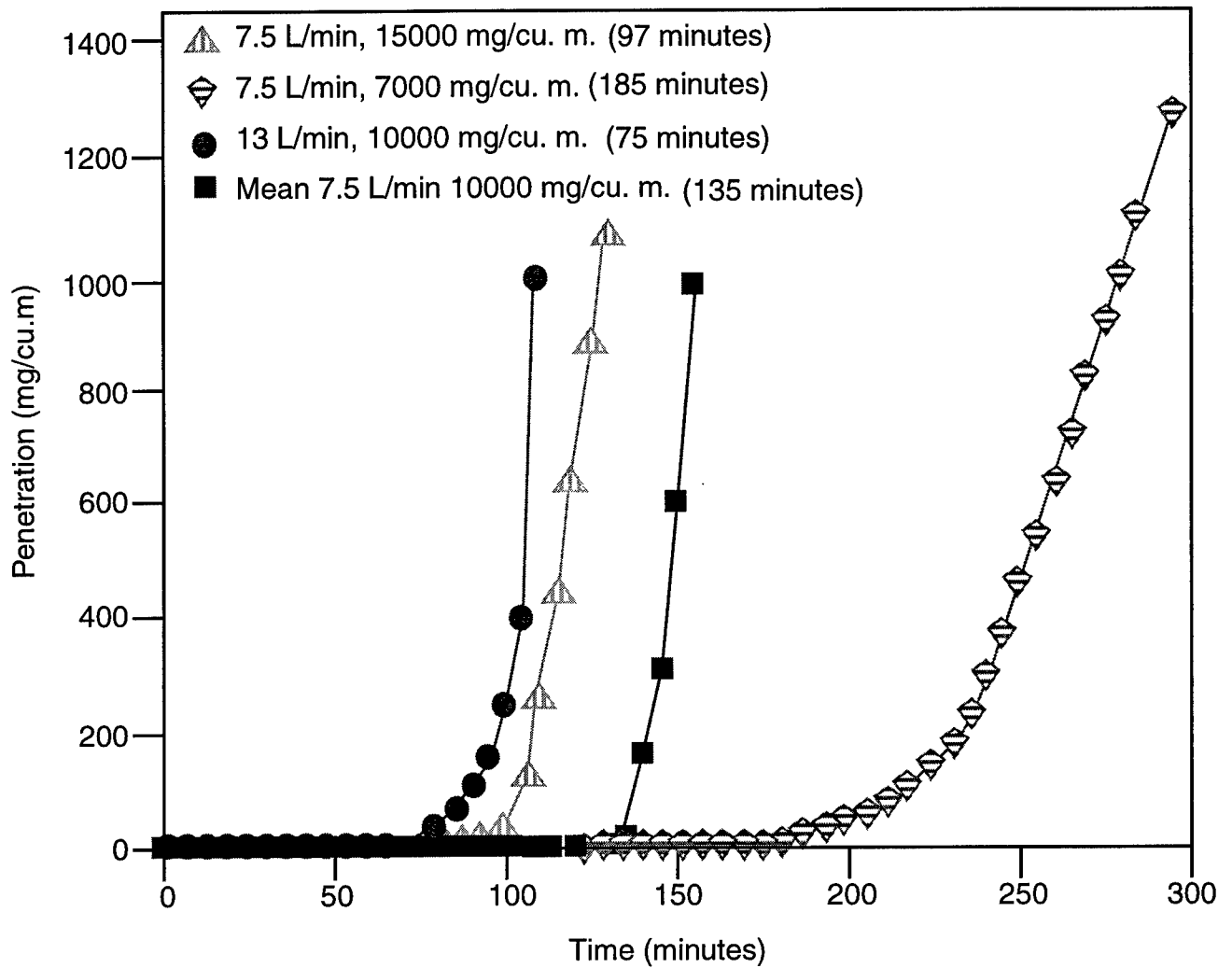


Figure 11

Breakthrough Profiles of Halothane on C2 Canisters
Containing ASC/T Carbon Under Various Challenge Conditions

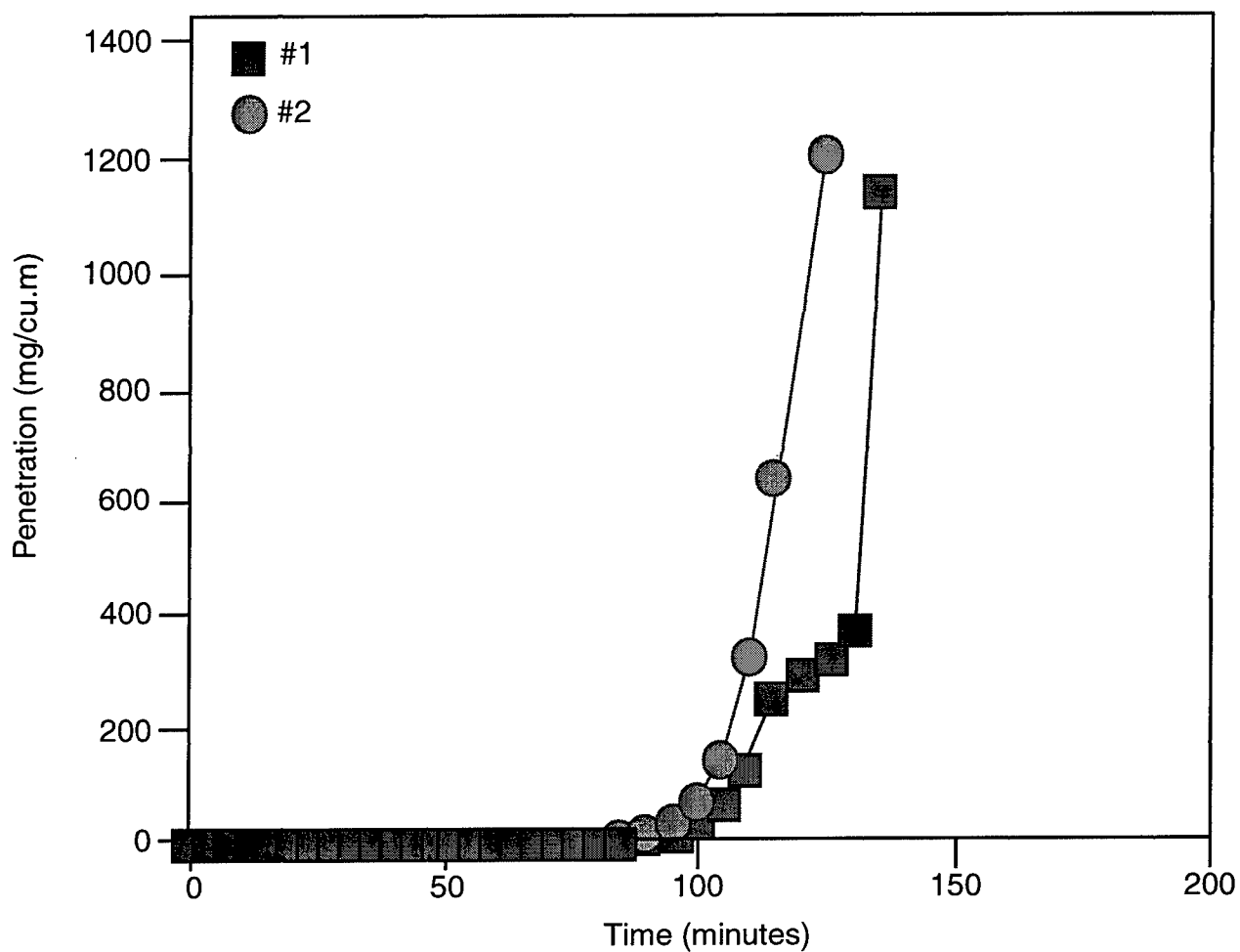


Figure 12

Breakthrough Profiles of Isoflurane on Half-Body C2 Canisters
Containing 6 X 16 Mesh BPL Carbon

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3. TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title.) Removal of Waste Anesthetics Exhaust (U)			
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This report describes the use of Canadian military carbon-containing canisters (C2 and C7) in removing waste anesthetics exhaust. The efficiency and service-life of these canisters are presented. In addition, the use of other adsorbents and some commercially-available occupational health and safety canisters for this purpose is also discussed.

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Anesthetics

Halothane

Isoflurane

Activated Carbon

C2 Canister

C7 Canister

Racal Health and Safety Filters

Removal of Waste

Coal-based Carbon

Cocunut-shell Based Carbon